15

Scientific Note E *February 1976*

NATURAL LIGHTNING PARAMETERS AND THEIR SIMULATION IN LABORATORY TESTS

By: E. T. PIERCE

Prepared for:

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
ARLINGTON, VIRGINIA 22217

CONTRACT N00014-74-C-0134

SRI Project 3062

STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) NATURAL LIGHTNING PARAMETERS AND THEIR SIMULATION IN LABORATORY TESTS	5. TYPE OF REPORT & PERIOD COVERED Scientific Note E
	6. ~~PERFORMING ORG. REPORT NUMBER~~ NR-082-206, SRI [redacted] 3062
7. AUTHOR(s) E. T. Pierce	8. ~~CONTRACT OR GRANT NUMBER(s)~~ N00014-74-C-0134 NR 082-206 Code 465
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stanford Research Institute, Menlo Park, California 94025	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Department of the Navy, Arlington, Virginia 22217	12. REPORT DATE Feb[redacted]976
	13. NO. OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS (~~if diff. from Controlling~~ Office)	15. ~~SECURITY CLASS.~~ (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

12 19p.

16. DISTRIBUTION STATEMENT (of this report)

DISTRIBUTION STATEMENT A

Approved for public release; Distribution Unlimited

...k 20, if different from report)

18. SUPPLEMENTARY NOTES "Natural Lightning Parameters and Their Simulation in Laboratory Tests" reprinted from Proceedings of the 1975 Conference on Lightning and Static Electricity (Culham Laboratory, England, April 1975) Session I, Paper 6, Royal Aeronautical Society, London, England.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lightning parameters	Thunderstorm statistics	Radio noise
Lightning simulation	Positive lightning flashes	Lightning specifications
Lightning incidence	Lightning models	
Lightning hazards	Lightning hazards to aircraft	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The paper summarizes our knowledge of natural lightning. The derivation of flash incidence from thunderstorm day statistics is first discussed. Information on lightning parameters is then reviewed; these parameters include peak current, rate of current rise, intermediate current, continuing current, action integral, and several others. Parameters of importance in aviation hazards are given particular attention.

(continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

over

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. KEY WORDS (Continued)

20 ABSTRACT (Continued)

The characteristics of positive flashes are examined, and the question of the representativeness of discharges to tall structures is considered. The electromagnetic fields radiated by close flashes are described. Finally, the realism of lightning models, specifications, and simulation tests, as they relate to natural lightning is critically discussed.

DD FORM 1 JAN 73 1473 (BACK)

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

NATURAL LIGHTNING PARAMETERS AND THEIR SIMULATION IN LABORATORY TESTS

E. T. Pierce
Stanford Research Institute, Menlo Park, California 94025, U.S.A.

Introduction

This paper summarizes--with critical asides--our present knowledge of lightning. It has two practical objectives. Firstly, it attempts to enable those concerned with operations involving aircraft and rockets to assess correctly the hazards associated with lightning. Secondly, it tries to define realistic criteria for laboratory simulation tests aimed at assisting designers in reducing lightning vulnerability.

The relevant literature is immense. Consequently, much of the material in this paper summarizes existing summaries! Also, the reference list is deliberately selective and illustrative rather than catholic and exhaustive.

When--as with the organization of this conference--a synopsis has to be written well in advance of the actual paper, reassessment often brings corrections. Specifically, the synopsis to this paper is misleading in two respects:

(1) In suggesting that the manner of current decay after the return-stroke peak is not of practical significance.

(2) In stating that the rise times as deduced for strikes to instrumented towers and to open country are significantly different.

Lightning Incidence

The first step in evaluating operational lightning hazards is to determine the lightning incidence within the specific operational area. If thunder is heard during a day, that day is reported meteorologically as a "thunderstorm day." The thunderstorm-day statistic is the only

parameter, readily available for any part of the world, from which lightning incidence can be assessed. If σ_y is the number of flashes per km^2 per annum and T_y is the annual number of thunderstorm days, then we may write

$$\sigma_y \approx C\, T_y^b \quad . \tag{1}$$

In Eq. (1), C and b are constants, whose values can be deduced from lightning flash-counter data.[1] Various investigations have yielded values of b ranging from 1.5 to 2. Nevertheless, some modern textbooks persist, with no justification, in incorrectly postulating a direct proportionality (b = 1) between σ_y and T_y. The reason that σ_y actually increases more rapidly than a direct proportionality with T_y is that in the more thundery regions the storms tend to be of longer duration and to have greater flashing rates. Monthly relationships (T_m, σ_m) have also been developed;[2] one such relationship[3] is

$$\sigma_m^2 = aT_m + a^2T_m^4 \tag{2}$$

where the flash density σ_m is per km^2 per month, T_m is the monthly number of thunderstorm days, and $a = 3 \times 10^{-2}$.

Flash densities (σ_y and σ_m) as derived from Eqs. (1) and (2) include both flashes to earth and intracloud discharges occurring above the square-kilometer area. The densities can be converted into densities of flashes to ground (σ_{yg}, σ_{mg}) by multiplying by the proportion, p, of discharges to earth. Although p has a great variability between individual storms and even between different phases of the same storm there is a systematic dependence on geographic latitude, λ, and thunderstorm days.[4,5] A convenient representation for p is

$$p^2 = \{p(T_y)\}\{p(\lambda)\} \tag{3a}$$

where

$$p(T_y) = \frac{1}{2 + 0.05\,T_y} \tag{3b}$$

and

$$p(\lambda) = 0.1\{1 + (\lambda/30)^2\} \tag{3c}$$

with λ in degrees.

In order to estimate the incidence of flashes to an actual object--aircraft in flight, ground tower, and so on--the attractive area needs to be known. The attractive area is the area over which lightning is diverted to the object by streamers induced from the object under the

influence of the lightning leader. The attractive area can be deduced empirically or derived theoretically.[6] There are uncertainties in the latter calculations--for example, our lack of any precise knowledge of leader charge distribution. The attractive area is sometimes very considerably larger than the geometric cross section, as in the case of a ground tower.

The incidence of flashes to an object is the product of the attractive area, the appropriate flash density (σ), and the time of exposure. Thus an aircraft of attractive area A parked in the open for 3 days a month, would encounter only flashes to ground, and a consequent monthly flash incidence of $A\,\sigma_{mg}\,(3/31) = A\,p\sigma_{m}\,(3/31)$.

In the case of large or elongated objects the flash incidence can be much augmented by the initiation (triggering) of flashes by the object itself.[7,8]

Types of Flashes

Those practically concerned with minimizing lightning hazards need consider only the two main types of discharge--the intracloud flash and the flash to ground. All flashes are probably initiated within the cloud in restricted areas of very high electric field. Typically, these areas are concentrated around an altitude of some 3 km with the cloud base being at 1 km. It follows that the probability of an aircraft intercepting a flash to ground is almost uniform from 0 to 3 km and then drops off sharply with increasing altitude. Intracloud discharges begin to be encountered at 1 km. They are experienced more frequently as altitude increases, and as the 3-km level is approached the chances of meeting an intracloud flash or a discharge to ground are about equal. The maximum incidence of intracloud flashes is at about 6 km, and few intracloud flashes reach to the cloud top ($\sim$12 km).

Electrically, intracloud flashes and discharges to earth have one major difference. The latter type contain return strokes within which very high peak currents ($i \sim 100$ kA) and rates of current rise ($di/dt \sim 100$ kA/μs) are experienced. There are no true return strokes, with their associated large values of i and di/dt, in intracloud discharges.

The deleterious effects of lightning are conveniently separated into four categories associated with distinct electrical causes.[9]

These are:

(1) Thermal vaporization and magnetic forces. Cause: return-stroke current of the order of tens of kiloamperes.

(2) Undesirable electromagnetic coupling from direct strokes. Cause: rates of current change typically tens of kiloamperes per microsecond.

(3) Burning and erosion. Cause: intermediate currents of the order of kiloamperes for milliseconds. Also, continuing currents of the order of hundreds of amperes for hundreds of milliseconds.

(4) Electromagnetic coupling from flashes that are "near misses."

Both intracloud discharges and flashes to earth are almost equally potent as regards Effect 3. For Effect 4, over most frequencies there is little difference between the two types of discharge. However, Effects 1 and 2 are dominantly produced by return strokes and therefore by flashes to earth. Tests geared to the severity of flashes to ground will also cover intracloud discharges.

Statistics of Lightning Parameters

Many lightning parameters are of little importance in causing hazards. These parameters include the total duration of discharges; the number of, and intervals between, return strokes in a flash to ground (provided it is recognized that more than one return stroke usually occurs); and the number and current waveforms of the K current surges in intracloud discharges. The descriptions of these parameters in existing texts[10] and surveys[2] are quite adequate.

Some other parameters are of much greater importance, and for these parameters our knowledge must be constantly updated. Two important parameters for the return stroke in the flash to earth are the peak current, i_p, and the rate of current rise, di/dt. The latter is variously--and often imprecisely--defined, but the most appropriate definition[2] is the average value of di/dt over the rise (front) time T_F from $i = 0$ to $i = i_p$. Another important return-stroke parameter is the half-value time occupied in decaying from the peak i_p to $i = 0.5\ i_p$. The statistics of return-stroke parameters are represented in Figure 1 for the usual flash transporting negative charge to ground. The representation is conveniently formulated in terms of the log-normal distribution; this distribution is closely obeyed by many parameters. Figure 1 terminates (as do Figures 2 and 3) at the 2% point; the distribution is easily extrapolated to more extreme values, but the greater the extrapolation the greater the uncertainty.

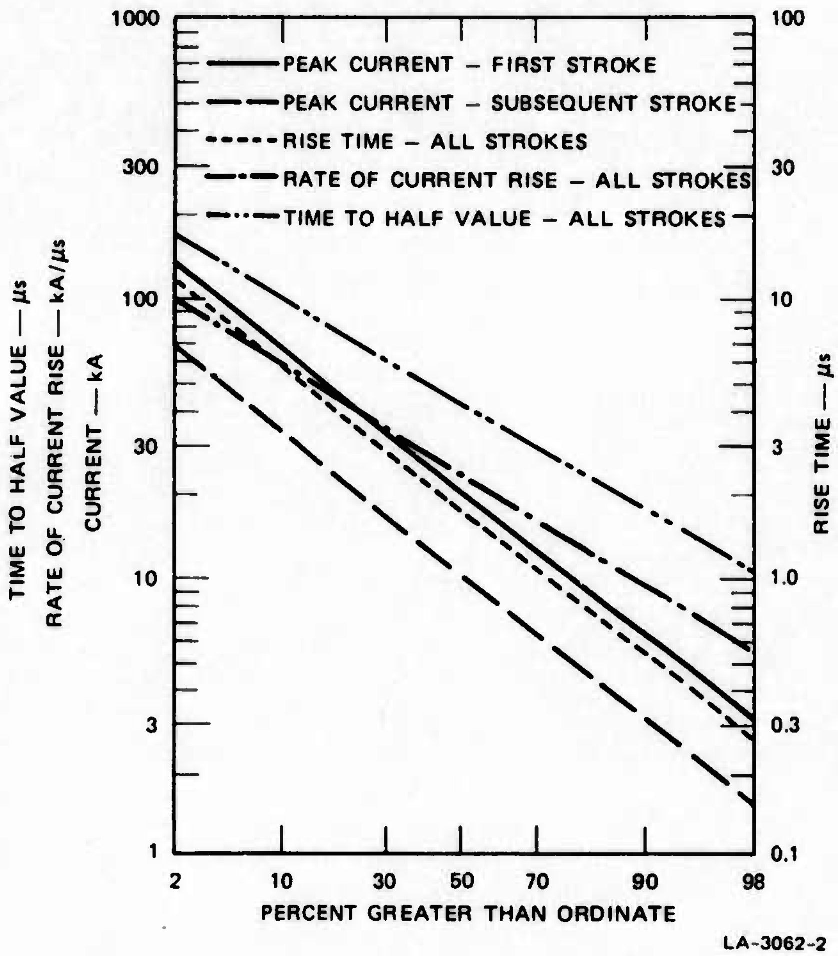

FIGURE 1 STATISTICS FOR RETURN-STROKE PARAMETERS – NEGATIVE STROKES

The main surge of return-stroke current is usually followed by an "intermediate" current of a few kiloamperes lasting for a few milliseconds. Although measurements of intermediate currents have been made, and characteristics of the currents have been deduced from observations of atmospherics, no statistical information on intermediate currents is readily available.[2] This is regrettable, since it is believed[11] that intermediate currents are the most likely type of current to produce metallic puncture when--as is common with aircraft--the point of flash attachment is being swept by the windstream.

Most discharges include a phase of continuing current. Intracloud flashes consist predominantly of continuing current; the superimposed K recoil surges represent only minor perturbations. Even for the discharges to ground, continuing currents rather than return-stroke surges produce most of the charge transfer. Statistics for continuing currents are shown in Figure 2.

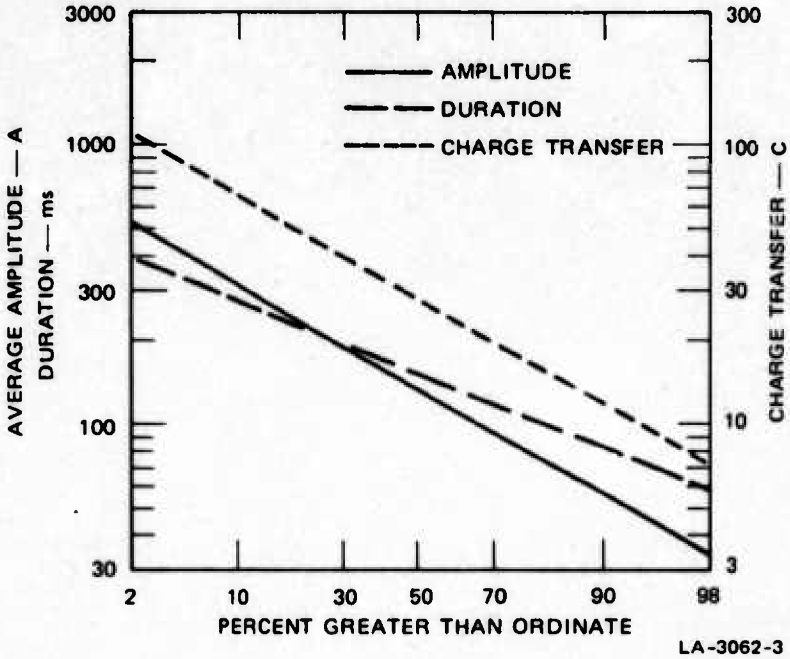

FIGURE 2 STATISTICS FOR CONTINUING CURRENTS – NEGATIVE FLASHES TO GROUND

Many lightning parameters are derived, rather than basic. Two of these, often quoted by engineers, are the total charge transfer Q per flash ($\int i \cdot dt$), and the total action integral, I, per flash ($\int i^2 \cdot dt$). Distributions for these parameters are given in Figure 3. Note that the distribution for total charge transfer is rather more extreme than that for the charge passing in continuing currents, although most charge in a typical flash flows during a continuing current. Some flashes, however, contain no continuing current phase at all, while some may include two or more such phases. These facts account for most of the difference between the two charge distributions.

Correlations between various lightning parameters have been investigated.[12,13] It is often incorrectly stated that a large value of i_p is associated with a short rise time T_F and therefore with an extremely high di/dt. In reality, in negative flashes the correlations between i_p and T_F and between i_p and di/dt are only marginally significant for first strokes and well below accepted significance levels for subsequent strokes.[13] Total charge transfer, Q, since it is predominantly in continuing currents, is essentially uncorrelated with i_p, T_F, or di/dt. The action integral evaluated over the high return-stroke current phase alone[12] is strongly correlated with i_p; this, of course, is to be expected. Surprisingly enough, the dominance of the first return-stroke contribution to I is such that there is some correlation between i_p and the total action integral, I, evaluated over the entire flash. A very rough relationship is

$$I \approx 5 \times 10^{-5}\, i_p^2 \quad . \qquad (4)$$

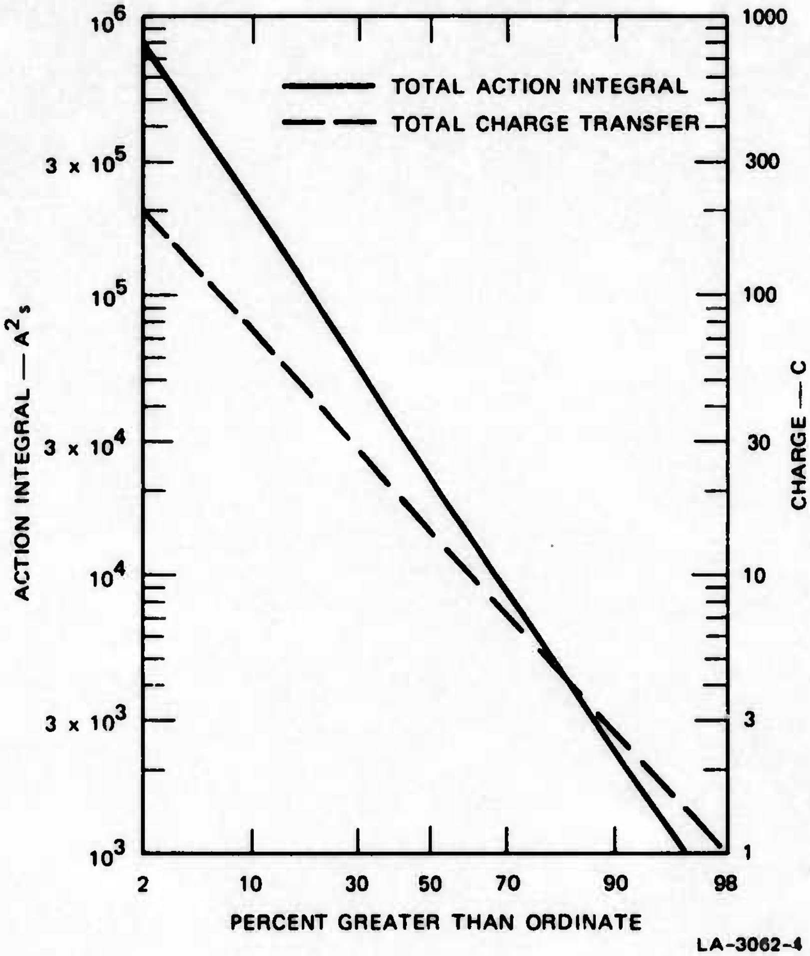

FIGURE 3 FURTHER STATISTICS – NEGATIVE FLASHES TO GROUND

Positive Flashes

Less than 10% of flashes to open ground carry positive electricity to earth.[2] However, for a tower of effective height of some 300 m the proportion increases to about 20%,[12] while over 40% of the discharge to captive balloons (tether lengths on the order of 1 km) are positive.[14]

There are indications that positive flashes tend to greater extremes than do negative discharges. This tendency is illustrated in Table 1. Table 1 shows that both for Monte San Salvatore and the tethered balloons the positive discharges give a larger proportion of both high and low currents than do the negative flashes; in other words the positive flashes are more extreme at both ends of the distribution. The very high percentage of extremely small currents for the tethered balloon is interesting. Probably a very long object electrically connected to earth initiates many

Table 1

STATISTICAL DISTRIBUTION (PERCENTAGES)
OF PEAK LIGHTNING CURRENTS

Reference	Data	Current (kA)	
		< 2	> 40
2	World-wide open ground		
	First return stroke (negative)	0.8	23
	Subsequent return stroke (negative)	4.0	6
12	Monte San Salvatore (negative)	0.2	13
	Monte San Salvatore (positive)	4.0	40
14	Tethered balloon (negative)	54	1
	Tethered balloon (positive)	69	4

low-current streamers that fail to develop into full-scale discharges. Such streamers occur often from Monte San Salvatore but tend to be ignored in Berger's statistics.[12,13]

Are Flashes to Tall Structures Representative?

Most of our detailed knowledge of lightning current waveforms is due to the phenomenal work of Berger.[12] In his observations at Monte San Salvatore he has used instrumented towers whose "effective" (tower and mountain) height is about 300 m. Consequently, in many respects the flashes studied by Berger differ from those to flat terrain. For example, as compared with normal flashes, Berger's discharges contain a very high proportion of flashes initiated (triggered) at the towers, include a large percentage of positive discharges, and contain few subsequent strokes.

Uman and his associates[15] have very much improved techniques for the deduction of current-time curves from observations of the electric and magnetic fields created by return strokes to open country. Their results can be compared with those of Berger. A comparison for i_p is given below. The open-country results seem to give the higher values of i_p, but this effect is more apparent than real since the data of Uman et al.[15] are a combination of two widely different samples that straddle the results of Berger.

Table 2

STATISTICS OF LIGHTNING PEAK CURRENTS (i_p)

Percentages exceeding indicated current values)

Data	Current (kA)				
	10	30	50	70	90
Berger[12]--all negative strokes	78	23	8	4	2
Uman et al.[15]--all strokes (presumably mostly negative)	82	43	19	10	4

The rise time also does not appear to show really significant differences. Berger's data[13] for negative flashes give median rise times of about 6 μs and 1 μs for first and subsequent strokes, respectively. The early results from the open-country work suggested that the rise time for the first stroke was more rapid and approached that for subsequent strokes. However, the later work[15] gives examples with rise times for first strokes ranging from 3 to 7 μs, and for subsequent strokes from 1 to 4 μs; the typical range for all strokes is quoted as 0.5 to 5 μs. These results are not greatly different from those of Berger.

Note that there is now fairly general agreement[12,15] that rise times in subsequent strokes may be as fast as 0.5 μs or less. Also, at the fast end of the distribution, the rise times in first strokes tend to exceed those in subsequent strokes by a factor of at least two. Since i_p in a subsequent stroke averages about 50% of that in a first stroke, it follows that the largest values of di/dt are likely to be encountered in subsequent strokes. This indeed is the practical experience of Uman et al.[15] It further follows that the rise time of the first stroke is more of academic than of practical engineering interest.

Finally, in this section, it is worth emphasizing that the open-terrain work[15] indicates a time to half-value of only 10 μs. This is significantly less than the generally accepted 40 μs.

Fields Due to Close Discharges

A complete lightning flash consists of many types of subsidiary sparks and arc discharges; the different types vary immensely in their characteristics. In consequence, the structure of the electric and

magnetic fields that are generated, is--as has been pointed out by Cianos et al.[16]--extremely complicated. For example, at frequencies below perhaps 100 Hz signals are produced almost throughout the entire discharge by continuing currents; at VLF (3 to 30 kHz) the field impulses tend to be discretely associated with return strokes and K recoil streamers; while at HF and VHF (3 to 300 MHz) thousands of pulses are radiated whose origin is probably in leader-streamers, although this has yet to be exactly established.

It is well known[16] that the fields generated by a radiating spark can be separated into "near-field" ($d < c/2\pi f$) and "far-field" ($d > c/2\pi f$) categories, where d is the distance from the radiator, c is the velocity of light, and f is the frequency. The electrostatic and magnetostatic terms dominate in the near-field regime; the radiation component is the largest in the far-field regime.

Very sensitive electronic devices are now used in rockets and aircraft. Also, the composite materials employed in modern aircraft construction are relatively ineffective in electromagnetic shielding.[17] It follows that the vulnerability to the fields produced by a lightning "near miss" is increasing.

The calculation of these fields is quite involved because the linear dimensions of the radiating channels are comparable with, or greater than, the distance involved in a near miss. There is also a complicated interplay among distance of radiators, frequency, and near- or far-field regimes.

Figure 4 is an estimate of the spectral distribution of the fields experienced close to modeled severe flashes. For the discharge to ground, the distance of 300 m is along the surface of the earth; for the intracloud flash it is from the mid-point of the channel.

Lightning Models, Specifications, and Simulation Tests

There was much discussion at the Las Vegas Conference[18-21] on these interrelated topics, with special focus on the Military Specification MIL-B-5087B(2). The following comments further pursue some of the points raised in the Las Vegas discussion:

(1) Over-Severity. Most specifications and models employ severe lightning parameters. As Holder[20] and Robb and Plumer[18] have emphasized, it is unrealistic to apply these parameter values equally to current entry at all points of an aircraft. Such application can only result in excessive protection and unnecessary expense.

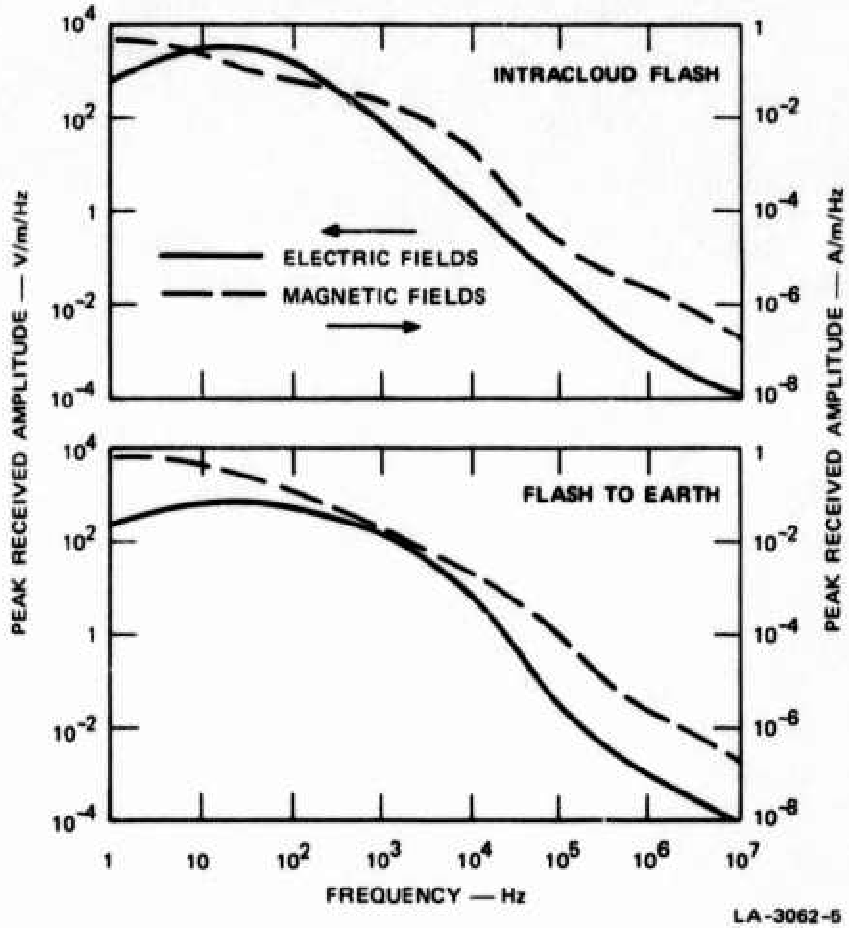

FIGURE 4 SPECTRAL DISTRIBUTION OF FIELDS EXPERIENCED 300 m FROM A SEVERE FLASH

A point hitherto not considered is that the changing operational practices for aircraft imply alterations (and often reductions) in lightning hazards. Furthermore, since operational practices vary very considerably with different types of aircraft, the same degree of hazard is not universally encountered. For example, a high (~200 kA) return-stroke current is unlikely to be experienced except by an aircraft flying in a thundery environment at an altitude of less than some 3 or 4 km. If the operational practices of the aircraft are such that this situation seldom occurs, the protection against large peak current (i_p) and rates of rise (di/dt) could be much reduced. The probable operational pattern, and its consequences in lightning exposure, should be considered for all types of aircraft. Only then can an acceptable balance be struck between risk and cost of protection.

(2) Deficiencies of Specifications. Specifications are often too precise in some respects and too vague in others. For example, MIL-B-5087B(2), is both precise (i_p = 200 kA) and vague (width of 5 to 10 μs at 90% points; not less than 20 μs at 50% points; rate of rise at least 100 kA/μs). The time history specified in MIL-B-5087B(2) could actually be satisfied by rise times ranging from the infinitesimal to the infinite!

The statistics of lightning (Figures 1, 2, and 3) and the resulting time and current tolerances are seldom discussed.[20] Only a severe waveform is usually specified, and consequently there is an understandable but regrettably misleading tendency to accept the severe as typical.

Occasionally, empirical mathematical representations are given with no indication of their limitations. The uninitiated are prone to believe--entirely incorrectly--that all flashes conform rigidly to the empirical definitions. Sometimes the representations are misleading. Thus, the well-known double exponential empirical equation[2] for the lightning current gives a convex form during the rising phase; in reality, the rise is usually either concave (first stroke) or straight-line (subsequent stroke).

(3) Test Procedures. A single test waveform should not be expected to simulate exactly a model or specification lightning representation. This would certainly be expensive and technically very difficult. The representation is to be regarded only as a guide, and the realistic approach will usually be to examine the main features of the representation (peak current, continuing current, and so on) successively in different individual types of tests. Flexibility should be permitted in these individual tests; thus, although the lightning current is not oscillatory, it seems satisfactory to test for i_p or di/dt using damped oscillatory waveforms.[11,20]

(4) Lightning Models. Models and specifications should, as emphasized by Evans and Phillpott,[21] certainly include all three phases: high current (and high rate of rise), intermediate current, and continuing current. It is now believed[11] that burning is not directly related to total charge transfer. Therefore, models should be defined in terms of current time history, and charge transfer should be regarded as a derived rather than a fundamental quantity.

Models and specifications should set values for the parameters at approximately the same statistical level. Intelligent

adjustments will, of course, be necessary for parameters that are partly interconnected. As an example, at the 2% severity level, Figures 1 and 2 suggest $i_p \sim 100$ kA, di/dt ~ 100 kA/μs, and a continuing current of $\sim$400 A for $\sim$300 ms .

Some models previously suggested seem statistically uneven in the values of the parameters they advocate. Thus, Perry[19] suggests $i_p = 200$ kA, $T_F = 15$ μs, and a continuing current of 500 A for one second. In relation to an i_p of 200 kA, 15 μs is far too long for the rise time, while the continuing current is overly severe. Evans and Phillpott[21] give $i_p = 200$ kA, $T_F = 15$ μs, and a following intermediate current taking 30 ms to decay from 30 kA to zero. Again T_F is too long for an i_p of 200 kA. Also, the suggested intermediate current is fantastically severe. This may be because the intermediate current is based on Berger's results for positive strokes;[12] there are reasons to believe[2] that the initiation of these strokes is so governed by special circumstances at San Salvatore that they are quite unrepresentative of the positive flashes (themselves rare) to open terrain.

In conclusion, Figure 5 shows a model representation of a very severe lightning flash devised in connection with work on Space Shuttle.[11] The model parameters are selected to be at comparable statistical levels. The representation is intended only as a guide and has therefore been much simplified in both physical and analytical respects. For instance, straight lines connect the key points (A, B, C, etc.) in the current time history. However, oversimplification is usually preferable to unjustifiable overcomplication.

Acknowledgments

I am very grateful to my associates Dr. N. Cianos and Mr. G. H. Price for their background contributions to this paper. I am also indebted to my colleague Dr. J. E. Nanevicz for undertaking, if necessary, to present this paper at Culham.

The preparation of the paper was supported by the U.S. Office of Naval Research under Contract N00014-74-C-0134. Accordingly, reproduction in whole or in part is permitted for any purpose of the U.S. Government.

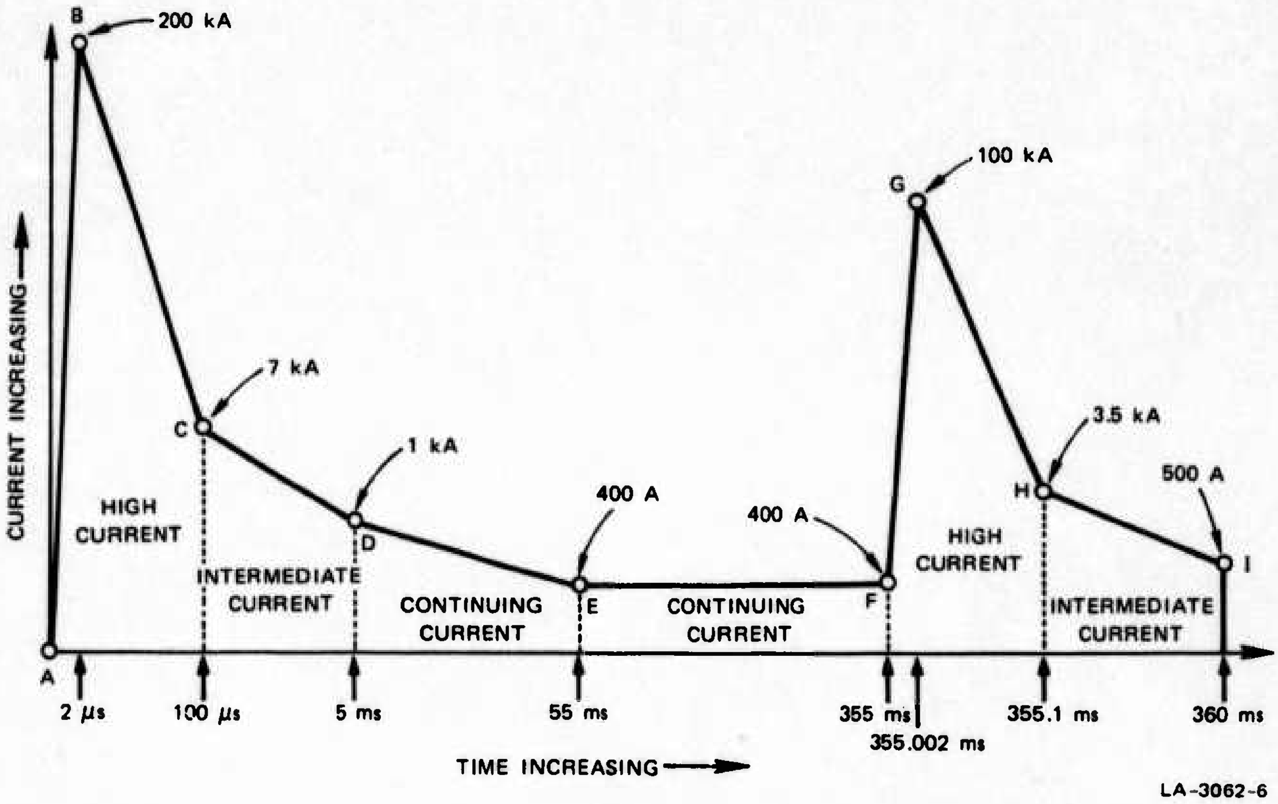

FIGURE 5 SEVERE LIGHTNING MODEL FOR SPACE-SHUTTLE WORK

References

1. ANDERSON, R. B., The Application of Lightning Flash Counters to the Determination of Thunderstorm Parameters, Special Report ELEK 54, Council for Scientific and Industrial Research, S. Africa, 1974.

2. CIANOS, N. and PIERCE, E. T., A Ground Lightning Environment for Engineering Usage, Technical Report 1, SRI Project 1834, Stanford Research Institute, Menlo Park, Calif., August 1972.

3. PIERCE, E. T., A Relationship Between Thunderstorm Days and Lightning Flash Density, Transactions of the American Geophysical Union, Vol. 49, p. 686, 1968.

4. PIERCE, E. T., Latitudinal Variation of Lightning Parameters, Journal of Applied Meteorology, Vol. 9, p. 194, 1970.

5. PRENTICE, S. A. and MacKERRAS, D., The Ratio of Cloud to Cloud-Ground Flashes in Thunderstorms, to be published in Journal of Applied Meteorology. Presently available as a document submitted to meeting of C.I.G.R.E. Task Force on Lightning Flash Counters, August 1974.

6. GOLDE, R. H., The Lightning Conductor, Journal of the Franklin Institute, Vol. 283, p. 451, 1967.

7. PIERCE, E. T., Triggered Lightning and Some Unsuspected Lightning Hazards, Naval Research Reviews, Vol. XXV, No. 3, p. 14, 1972.

8. SHAEFFER, J. F., Aircraft Initiation of Lightning, p. 192, Proceedings of 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.

9. AMASON, M. P., CASSELL, G. J., KUNG, J. T., LaMANNA, J. A., and McCLOUD, W. W., Aircraft Lightning Protection Design Considerations, p. 214, Proceedings of 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.

10. UMAN, M. A., Lightning, McGraw-Hill Book Co., Inc., New York, N.Y., 1969.

11. __________, Space Shuttle--Lightning Protection Criteria Document Report No. JSC-07636, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, 1973.

12. BERGER, K., Methods and Results of Research on Lightning on Mount San Salvatore 1963-1971, Schweizerischer Elektrotechnischer Verein Bulletin, Vol. 63, pp. 1403-1422, 1972.

13. KRONINGER, H., Further Analysis of Professor Berger's San Salvatore Lightning Current Data, Special Report ELEK 53, Council for Scientific and Industrial Research, S. Africa, 1974.

14. DAVIS, R. and STANDRING, W. G., Discharge Currents Associated with Kite Balloons, Proceedings of the Royal Society, London, Vol. A191, p. 304, 1947.

15. UMAN, M. A., McLAIN, D. K., FISHER, R. J., and KRIDER, E. P., Currents in Florida Lightning Return Strokes, Journal of Geophysical Research, Vol. 78, pp. 3530-3537, 1973.

16. CIANOS, N., OETZEL, G. N., and PIERCE, E. T., Structure of Lightning Noise--Especially Above HF, p. 50, Proceedings of the 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.

17. FISHER, F. A., Electromagnetic Shielding Properties of Composite Materials, p. 306, Proceedings of the 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.

18. ROBB, J. D. and PLUMER, J. A., Introduction of the Session on Lightning Simulation, Testing, and MIL-B-5087B, p. 593, Proceedings of the 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.

19. PERRY, B. L., British Civil Airworthiness Requirements for Electrical Bonding and Lightning Discharge Protection in Relation to Specification MIL-B-5087, p. 595, Proceedings of the 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.

20. HOLDER, F. P., Comments on MIL-B-5087B(2) Bonding Electrical and Lightning Protection for Aerospace Systems, p. 613, Proceedings of the 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.

21. EVANS, R. H. and PHILLPOTT, J., Lightning Simulation and Testing in Relation to Specification MIL-B-5087, p. 616, Proceedings of the 1972 Lightning and Static Electricity Conference, Air Force Avionics Laboratory, 1972.